OVERVIEW OF STRUCTURAL DAMAGE TOLERANCE HISTORY AND TRENDS

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INTRODUCTION

The following presentation briefly overviews the history of airframe damage tolerance and reflects on some perceived trends in this area. It is based on this National Resource Specialists perspective and should not be interpreted as official FAA position or policy.

The National Resource Specialist program was established in 1979 and was implemented to attract and maintain a group of technical experts in various core disciplines whose technical expertise could be drawn on, as required, by the FAA, other U.S. Government Agencies, foreign civil aviation authorities and the aviation industry. Nineteen (19) technical disciplines have been identified which includes Fracture Mechanics. Other structures related disciplines are Flight Loads/Aeroelasticity, Nondestructive Evaluation, Metallurgy, Advanced Composites, and Crash Dynamics. You are encouraged to take advantage if this resource.

ALOHA 737 - APRIL 1988

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A discussion on airframe damage tolerance would not be complete without some mention of the Aloha 737 incident. This always stimulates thinking on the many different aspects of damage tolerance. The damage seen here was precipitated by the existence of relatively small multisite cracks at fastener holes in a fuselage longitudinal splice. The structure was intolerant to this damage and a large portion of the fuselage above the floor was lost during flight. Fortunately, the remaining structure had enough inherent tolerance to this large damage for the aircraft to land, although one life was lost. This incident, combined with increasing concern with respect to the potential impact of undetected multisite fatigue damage, was the catalyst for the aging aircraft initiatives which were launched shortly afterwards.

PRE 1974 DESIGN PHILOSOPHIES

- ADEQUATE STATIC STRENGTH PROVIDED BY DESIGNING UNDAMAGED STRUCTURE TO WITHSTAND SPECIFIED CONDITIONS, FACTORED BY 1.5, WITHOUT FAILURE
- ADEQUATE SERVICE LIFE INSURED BY SAFE-LIFE DESIGN
- MULTIPLE LOAD PATH DESIGN EMPLOYED TO ENHANCE SAFETY, AS A STANDARD PRACTICE, AND/OR AS A CERTIFICATION ALTERNATIVE TO SAFE-LIFE - (THIS PHILOSOPHY WAS TYPICALLY APPLIED BY EVALUATING STRENGTH CAPABILITY WITH A SINGLE LOAD PATH OMITTED WITHOUT CONSIDERING DAMAGE IN THE SURROUNDING STRUCTURE)

PRE 1974 DESIGN PHILOSOPHIES

Prior to 1974 there were three primary design philosophies used for aircraft. First, basic static strength was insured by designing well (or undamaged) structure to be able to withstand, without catastrophic failure, specified design (i.e. limit) conditions factored up by 1.5. This practice had been successfully used for many years to preclude single loading event failures within the operating design envelope. Concerns over premature loss of structural integrity due to fatigue were the motivation for use of the safe-life philosophy wherein the structure was designed to be free from detectable cracks for a certain period of time (i.e. design life goal). Application of this approach required testing for periods significantly in excess of the design life goal. The third philosophy involved the use of multiple load paths and was standard practice by many companies to provide extra forgiveness in the presence of unplanned damage. The multiple load path or “fail-safe” approach was also an option, provided in the original version of FAR 25.571, to certification as safe-life. In practice this approach involved assessing load carrying capability with a single element omitted without considering coexisitng damage in the adjacent structure.

RELEVANT SERVICE EXPERIENCE

(THRU 1977)

- **SIGNIFICANT/CATASTROPHIC FATIGUE CRACKING, ON AIRCRAFT DESIGNED AND TESTED USING SAFE-LIFE APPROACH, DUE TO LESS THAN PLANNED FOR INITIAL MANUFACTURING QUALITY**
  - KC-135, F-5, F-111, ,C-133
- **LOSS OF AIRCRAFT DUE TO FAILURE OF "FAIL-SAFE" MUTIPLE LOAD PATH STRUCTURE AS A RESULT OF UNDETECTED MULTI-SITE CRACKING**
  - HAWKER SIDDLEY 748 (ARGENTINA, 1976)
  - B707 (ZAMBIA, 1977)
- **SAFE RETURN OF AIRCRAFT, WHICH HAD SUFFERED SIGNIFICANT AMOUNTS OF DAMAGE, BECAUSE OF INHERENT DAMAGE TOLERANCE**
  - TOUGH MATERIALS (E.G. 2024-T3)
  - BUILT-UP, CONVENTIONALLY FASTENED ASSEMBLIES

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RELEVANT SERVICE EXPERIENCE

Service experience demonstrated the strengths and weaknesses of the design philosophies which had been used to address loss of structural integrity due to damage (e.g. fatigue cracking). Incidents of fleet wide cracking and catastrophic loss of aircraft experienced by the Air Force was painful evidence that the safe-life philosophy by itself was inadequate. The failure to address less than planned for initial manufacturing quality was at the root cause. Confidence in the multiple load path or "fail-safe" approach was also shaken when aircraft were lost due to the unexpected catastrophic failure of "fail-safe" structure. Undetected cracking resulting from lack of inspections consistent with structural damage tolerance characteristics was the root cause. On the positive side were a significant number of incidents where aircraft safely landed after having experienced major inflight damage (e.g. fuselage damage due to propeller loss). This success can be attributed to the inherent damage tolerance of the materials used and the multiple load path design which was employed.

LESSONS LEARNED

- FAILURE TO DESIGN AND/OR ESTABLISH INSPECTION PLANS BASED ON THE ASSUMPTION THAT UNPLANNED STRUCTURAL DAMAGE WILL OCCUR CAN LEAD TO UNSAFE CONDITIONS
- "FAIL-SAFE" DESIGN WITHOUT CORRESPONDING DIRECTED INSPECTIONS, AT APPROPRIATE INTERVALS, IS NOT TRULY <u>FAIL-SAFE</u>
- FATIGUE CRACKING AT MORE THAN ONE LOCATION SHOULD BE ADDRESSED, ESPECIALLY AS THE AIRFRAME AGES
- MULTIPLE LOAD PATH STRUCTURE CAN PROVIDE A LEVEL OF INHERENT DAMAGE TOLERANCE SUCH THAT AN UNPLANNED IN-SERVICE MISHAP IS SURVIVABLE

LESSONS LEARNED

Service experience indicated that unplanned for damage (e.g. material defects, poor initial manufacturing quality, etc.) will occur and unless actions are taken to compensate for it safety may deteriorate to unacceptable levels. It also indicated that so called "fail-safe" design may result in a false sense of security and cannot, by itself, result in an adequate level of safety. Experience shows us that this is especially true as the aircraft ages and the probabilty of cracking at more than one location increases. Experience has also illustrated the virtues of multiple load path structure and its forgiveness with respect to unplanned for large scale damage.

FORMAL DAMAGE TOLERANCE REQUIREMENTS

- USAF MIL-A-83444, "AIRPLANE DAMAGE TOLERANCE REQUIREMENTS", ISSUED IN JULY 1974
  - APPLICABLE TO THE DESIGN OF ALL USAF AIRCRAFT
  - REQUIRES ASSUMPTION OF A ROGUE FLAW IN THE MOST CRITICAL AREAS OF ALL SAFETY OF FLIGHT STRUCTURE
  - REQUIRES RESIDUAL STRENGTH TO BE MAINTAINED TO MINIMUM LEVELS FOR MINIMUM TIME PERIODS DEPENDING ON DESIGN CONCEPT AND INSPECTABILITY
- FAA AMENDMENT 45 TO FEDERAL AVIATION REGULATIONS (FAR) PART 25 ISSUED DECEMBER 1978
  - APPLICABLE TO COMMERCIAL TRANSPORT AIRCRAFT
  - DAMAGE TOLERANCE EVALUATION REQUIRED
  - MINIMUM RESIDUAL STRENGTH LEVELS SET
  - REQUIRES ESTABLISHMENT OF INSPECTION PLAN CONSISTENT WITH DAMAGE TOLERANCE CHARACTERISTICS OF STRUCTURE

FORMAL DAMAGE TOLERANCE REQUIREMENTS

Formal damage tolerance requirements were adopted for the design of new aircraft in response to lessons learned. The Air Force issued MIL-A-83444 in July of 1974. This was intended for application to the design of all new USAF aircraft. It recognized the potential impact of less than planned for initial quality and required the assumption of a rogue flaw. It also linked inservice inspection requirements to the damage tolerance characteristics of the design by specifying minimum residual strength levels tied to inspection types and intervals. The FAA issued amendment 45 to Part 25 in December 1978. This was applicable to the certification of all new large commercial transport aircraft and mandated that a damage tolerance evaluation be performed. It requires minimum levels of residual strength to be maintained by establishing inspection plans consistent with the damage tolerance characteristics of the structure.

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CURRENT TRENDS

- INCREASING RECOGNITION OF THE IMPORTANCE OF ACCOUNTING FOR UNPLANNED DAMAGE

- INCREASING COLLABORATION BETWEEN DOD, FAA, NASA, INDUSTRY, ACADEMIA, ETC. WITH RESPECT TO ENHANCING DAMAGE TOLERANCE OF NEW AND EXISITING AEROSPACE SYSTEMS

- MORE WIDE SPREAD ADOPTION OF DAMAGE TOLERANCE REQUIREMENTS FOR NEW DESIGNS
  - ROTATING ENGINE COMPONENTS ?
  - ROTORCRAFT?
  - SMALL AIRCRAFT?

CURRENT TRENDS

The role of damage tolerance in the design of new structure and management of existing systems is in a state of flux. An increasing recognition of the importance of planning for the unplanned is drawing more and more attention to its value in maintaining and enhancing safety. Because of this we are seeing a new era of cooperation and collaboration between designers, operators, maintainers, regulators and researchers. It is believed that we will also see adoption of damage tolerance philosophies for other than military aircraft and large commercial transports. This may include rotating engine components, rotorcraft, and small aircraft.

CURRENT TRENDS (cont'd)

- USE OF DAMAGE TOLERANCE EVALUATION RESULTS USING WORST CASE MANUFACTURING DEFECT SIZES TO SET THRESHOLD POINT FOR INSPECTIONS?
- INCREASING ECONOMIC PRESSURES WORKING AGAINST ENHANCED DAMAGE TOLERANCE
  - PREMATURE USE OF NEW MATERIALS
  - PREMATURE IMPLEMENTION OF NEW MANUFACTURING PROCESSES
  - DESIGN FOR MANUFACTURE AND ASSEMBLY (DFMA) INITIATIVES RESULTING IN LARGE INTEGRAL COMPONENTS
  - COSTS ASSOCIATED WITH FULL SCALE FATIGUE AND DAMAGE TOLERANCE TESTING

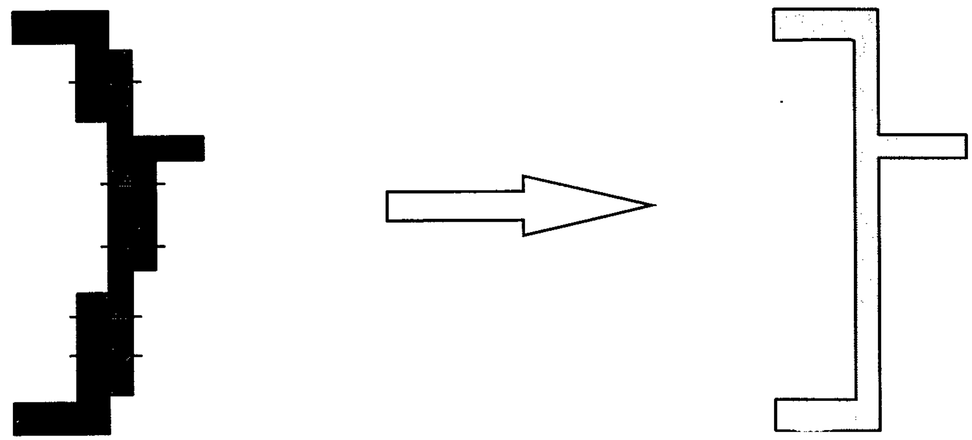
CURRENT TRENDS (cont'd)

There is a strong case to be made for setting initial inspection points for principle structural elements based on rogue flaw assumptions. This notion is not universally embraced. However, given enough time and some more adverse service experience, it may be.

Even with the increased sensitivity to the importance and value of the damage tolerance approach and trends towards expanding its application and use, there still are some factors that will challenge us in maintaining and enhancing damage tolerance in new systems. New untried and unproved materials will be proposed for cost and/or weight savings. New manufacturing processes intended to save cost will be proposed. Care must be taken to adequately understand their impact on damage tolerance so informed decisions can be made with respect to implementation. Designing for manufacture and assembly efficiency will result in large integral components which have less inherent damage tolerance. Finally, the costs associated with testing will work against having the comprehensive development and qualification basis needed to move forward confidently with new materials, manufacturing processes and design concepts. 226

INTEGRAL STRUCTURE

- INTEGRATING PARTS CAN SIGNIFICANTLY REDUCE ASSEMBLY COSTS



BUILT-UP INTEGRAL

- CRACK CONTAINMENT BY ARRESTMENT AND/OR CRACK TURNING IS DIFFICULT TO INSURE/VALIDATE
- PAST EXPERIENCE SHOWS THAT BUILT-UP STRUCTURE IS INHERENTLY MORE DAMAGE TOLERANT THAN ITS INTEGRAL COUNTERPART

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INTEGRAL STRUCTURE

Integrating structure can be a very efficient way to reduce system cost. Reduced part count and elimination of assembly steps can offer atractive savings. When this is done it must be recognized that extra care and effort must be given to understanding damage tolerance characteristics. Although crack containment and even arrest is possible to attain in integral strucutre it is difficult to insure and demonstrate with high confidence. The much greater inherent damage tolerance of built-up structure has proved its value in the past and shouldn't be overlooked when weighing recurring system costs against development costs and inherent system survivability. This is especially the case for structure which will be exposed to a known threat (e.g. burst engine disk, battle damage, etc.).

SUMMARY

- IN-SERVICE EXPERIENCE HAS DEMONSTRATED THE SHORT COMINGS OF THE SAFE-LIFE AND "OLD" FAIL-SAFE APPROACHES
- DAMAGE TOLERANCE REQUIREMENTS, ADOPTED FOR MILITARY AIRCRAFT DESIGN AND COMMERCIAL TRANSPORT AIRCRAFT CERTIFICATION, LINK DAMAGE TOLERANCE CHARACTERISTICS AND IN-SERVICE INSPECTION REQUIREMENTS
- INCREASED SENSITIVITY TO THE POTENTIAL IMPACT OF UNPLANNED DAMAGE SHOULD RESULT IN SAFER AEROSPACE SYSTEMS
- ECONOMIC PRESSURES WILL PRESENT SIGNIFICANT CHALLENGES WITH RESPECT TO IMPLEMENTION OF NEW DAMAGE TOLERANT DESIGNS

SUMMARY

Inservice experience has taught us the shortcomings of the safe-life and fail-safe design philosophies as applied in the past. This set the stage for adoption of damage tolerance based requirements for the design of USAF aircraft and later for the certification of large civil transport aircraft. This plus an ever increasing sensitivity to the potential impact of unplanned damage should result in wider application of damage tolerance principles and thus safer aerospace systems. However, care must be taken since economic pressures will continue to challenge us with respect to implementing new damage tolerant designs.